A Box to Measure RF Impedances

By G Billington, G3EAE*

THE BOX IN QUESTION IS an RF potentiometer designed for coaxial feeder impedance measurements in the range 5 to 600Ω. The impedances are calculated from voltage measurements, and the unit is designed to operate with a modern digital voltmeter with an input resistance of 10MΩ or more. A low power RF source capable of giving a couple of watts of harmonic free output into a load of around 50Ω is also required.

The box can be used in either a very simple or in a more sophisticated manner. It is small, cheap, and easy to build, and to a certain extent it is self checking. As well as measuring feeder input impedances it can be used to check the RF value of resistors against known capacitors and to measure RF impedances in general.

PRINCIPLE OF THE METHOD

THE BASIC POTENTIOMETER arrangement and the required measurements are shown in **Fig 1**. The unknown impedance 'Z' is connected in series with a known impedance 'S' to a suitable RF source. The three voltages V_s, V_z, V_{in}, are all measured as described later. 'Z' may then be found using the formula: $Z/S = V_z / V_s$

MEASURING FEEDER INPUT IMPEDANCE: A SIMPLE EXAMPLE

SUPPOSE THAT 'Z' is the input impedance of a coaxial antenna feeder and that a resistor of 56Ω is used as 'S'.

The measured voltages are:

$V_s = 5.0V$; $V_z = 2.5V$; $V_{in} = 7.5V$,

The unknown impedance 'Z' is given by:

$Z = 56 \cdot (2.5/5.0)$
$= 28\Omega$

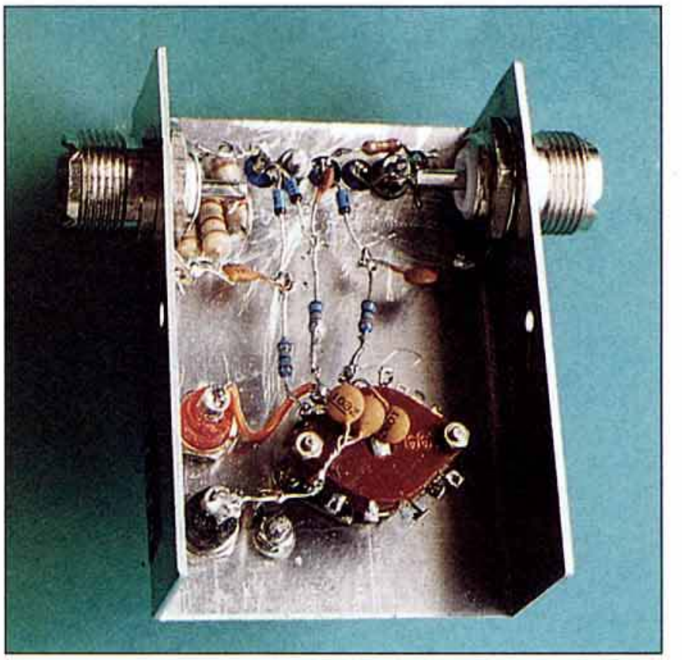
75 Mount Vernon Road, Barnsley, S. Yorks, S70 4DW.

Of course the important question is whether or not 'Z' is resistive. There is a simple test which will decide this. If $V_{in} = V_s + V_z$, 'Z' is a pure resistance.

Using the given figures: 7.5 = 5.0 + 2.5.

The figures pass the test and 'Z' is a pure resistance.

The procedures just described are easy to carry out and can give a quick reassurance that an antenna is behaving itself.



Internal view of the impedance measuring box.

CORRECTING THE READINGS

If 'S' is a resistance but 'Z' is complex, $(V_s + V_z)$ will be greater than V_{in} but whatever the nature of 'Z' it is not possible for $(V_s + V_z)$ to be *less* than V_{in}. Nevertheless, if the box is set up with 'S' and 'Z' both resistors, it will be found that $(V_s + V_z)$ *will* be less than V_{in} by about 0.15V. (This assumes that the recommended Schottky diodes have been used). If 0.15V is added to all readings, agreement becomes very satisfactory, usually within 0.05V. Using silicon diodes (1N914) the correction was in the region of 0.4V. It is surprising that a virtually constant correction works over the range one to twenty volts.

It will be found that correcting the readings will often have so little effect on the numerical value of 'Z' that it may not seem worth doing, but if you are going on to find the resistive and reactive components as described in the next section, these small corrections are more important.

FINDING BOTH COMPONENTS OF 'Z'

SUPPOSE NOW THAT V_z and V_s have the same values as before but that V_{in} is 6.5V. (Assume all readings have been corrected). As V_z and V_s no longer add directly to give V_{in} we know that 'Z' is not a pure resistance. However, 'Z' is calculated exactly as before: it is still 28Ω but is now a complex impedance. The values of the resistive and reactive components of 'Z' can be found by drawing a triangle as shown in **Fig 2**. The sides represent the three voltages with V_s drawn horizontally. The angle q is then measured. In this case it is 64°. Z may be represented either by the series combination R_s and X_s, or by the parallel combination R_p and X_p (**Fig 3**).

$R_s = Z\cos\theta$ $\quad R_p = Z/\cos\theta$
$X_s = \sin\theta$ $\quad X_p = Z/\sin\theta$
Using $Z = 28\Omega$, $\theta = 64°$
$R_s = 12\Omega$ $\quad X_s = 25\Omega$

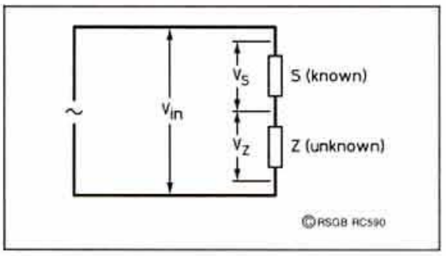


Fig 1: Basic potentiometer principle of the impedance measuring box.

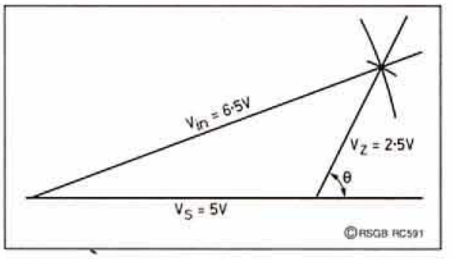


Fig 2: Extraction of Z components from voltage readings.

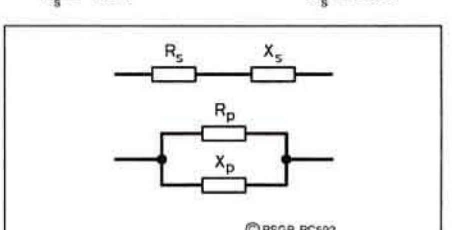


Fig 3: Series and parallel combinations of R and X.

Front panel of impedance measuring box showing the fixed reference connector block.

$R_p = 64\Omega$ $X_p = 31\Omega$

Unfortunately the method described does not tell us whether 'X' is inductive or capacitive. This can be done by making 'S' a known capacitor as described later.

If you do not want to draw a diagram to find θ it may be calculated:

$$\cos\theta = (V_{in}^2 - V_s^2 - V_z^2)/2V_s \cdot V_z$$

CONSTRUCTIONAL DETAILS

THE UNIT IS BUILT into a small metal box. The circuit is shown in **Fig 4**. It is a great advantage to mount 'S' externally using a PCB terminal block. All connections can be kept very short and 'S' can be changed at will. Two Maplin 2-wire 10mm PCB connectors (JX38R or JY93B) are used. The two blocks can be slotted together giving a longer block with four connecting points. This block is bolted down onto the exterior of the box using two 6BA nuts and bolts which must be passed through the two blank holes in the blocks.

A small amount of thin plastic has to be cracked off to allow the passage of the bolts. Each of the screw connectors carries a short wire projection which requires a hole boring so it can pass through into the interior of the box. One pair of the connectors is used to accommodate 'S'. The inner one of the other pair is labelled 'O' and goes to the coaxial output socket and the outer, labelled 'E' goes to chassis by the shortest possible route (**Fig 5**). When using the coaxial output, the neighbouring 'O' and 'S' points are connected by a short link.

When testing the device using resistors, capacitors, etc the link is removed and the test piece is connected between the inner 'S' connector and 'E'. Removing the link disconnects the capacitance of the output socket - about 4-9pF - which would otherwise be in parallel with the test piece. The inner 'S' connection will have to accommodate two wires, one from 'S' and the other either from the test piece ('Z') or from the link.

The above method of construction enables critical connections to be kept very short. It is important that the diode leads are soldered as close to the body of 'S' as possible, ie to the short wires which project from the connectors into the interior of the box. The actual length of the diode leads is not very critical so there is no need to cut them too short and risk cooking the diodes during soldering.

The resistors at the input are to prevent the load on the source exceeding 112Ω or going lower than 22Ω. These are extreme cases. In antenna measurements the load is likely to be closer to 50Ω and nearly all resistive.

The 22Ω resistor can be omitted if desired. Its only purpose is to prevent a short circuit in the unlikely event that 'S' and 'Z' together form a resonant series circuit, which just could happen if 'S' is a capacitor and 'Z' an inductor.

The input resistors also provide a DC leak across the line which is essential for the operation of the diodes. The 22KΩ resistor across the output ensures that there is such a leak under all conditions. Schottky diodes (BAR 28, Maplins QQ13P) are employed.

TESTING THE BOX USING RESISTORS

FIRST REMOVE THE LINK thereby disconnecting the output socket.

Another 1 watt resistor in the range 20 to 200Ω is chosen for 'Z' and is connected between the inner 'S' connector and 'E'. Both 'S' and 'Z' should have leads cut as short as possible. Maplin 1 watt resistors seem to be OK at HF, at least up to 14MHz, the highest frequency used.

Measure the voltages and check that:

1) $V_z/V_s = Z/S$
2) $V_z + V_s = V_{in}$

As explained earlier, better agreement is obtained if a small correction is added to every voltmeter reading. 0.15V was suggested, though in fact anything between 0.13 and 0.15 seems to be satisfactory. Correcting the readings should lead to a small but noticeable all round increase in accuracy, particularly when 'Z' is more than 4S or less than S/4.

Repeat these checks using different input voltages and different values of 'S' and 'Z'. Do not use inputs greater than 20V, and also try to avoid using any voltage reading lower than 1.0V. The diode response is particularly inaccurate at low voltages.

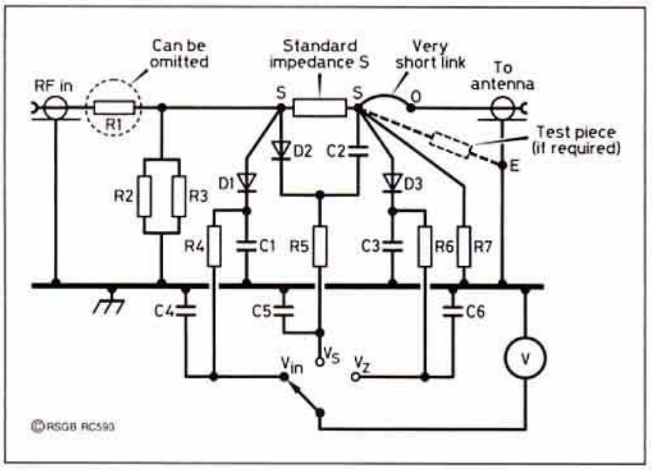


Fig 4: Circuit diagram of impedance measuring box.

USING THE BOX TO MEASURE Z_o AND VELOCITY FACTOR:

The characteristic impedance (Z_o) of a coaxial feeder and also its length in electrical degrees can be both found from the same two pairs of measurements. These are made on a length of the cable. The exact length is not critical but it should not be less than 1/16th of a wavelength, and not more than 3/16ths. Only one end should be fitted with a plug, at the other should be a clean cut.

The cable needs to be plugged into the output socket of the box. A resistance of around 56Ω is used as 'S'. The measurements V_s and V_z are then made:

1. With the far end open circuit and
2. With a good short circuit across the far end. One or two millimetres of the inner core can be exposed, and the braiding pulled over it and soldered or even clipped.

Let the open circuit value of V_z/V_s be denoted by 'P', and the closed circuit value of V_z/V_s be denoted by 'C'

$$Z_o = S \cdot \sqrt{(P.C)}$$

the angular length Ω is given by:

$$\tan\Omega = \sqrt{(C/P)}$$
$$\Omega = \tan^{-1}\sqrt{(C/P)}$$

If the actual length of the sample is 'L' metres, then each metre is equivalent to Ω/L electrical degrees.

The wavelength on the line λ_L is given by

$$\lambda_L = L \cdot (360/\Omega)$$

The velocity factor for the line is equal to the line wavelength divided by the free space wavelength λ_o

$$\text{Velocity factor} = \lambda_L / \lambda_o$$

FEEDER LENGTHS LONGER THAN ONE QUARTER WAVELENGTH

The above method can be employed using longer feeder lengths with the following limitations.

1. The length can be any integral number of half wavelengths *plus* a fraction of one quarter wavelength. The extra half wavelengths have no effect on the measurements.
2. If the length is any *odd* number of quarter wavelengths plus a fraction of a quarter wavelength, the ratio C/P must be inverted. In this case:

$$\tan\Omega = \sqrt{(P/C)}$$
$$\Omega = \tan^{-1}\sqrt{(P/C)}$$

In both the above cases Ω is the angular length of the final incomplete quarter wavelength which should be somewhere between 20 and 70°. If Ω lies outside these limits (ie if the feeder length is close to a whole number of quarter wavelengths) the results will be very inaccurate. In such cases the feeder should be extended by about one eighth of a wavelength before making measurements.

TESTING WITH CAPACITORS

A CAPACITOR MAY also be used as 'Z', and its reactance found. This is obtained in exactly the same way as with the resistors. The following points should be borne in mind when using a capacitor as 'Z':

1) The nominal value of the capacitance will be effectively increased by 4 or 5pF due to the output capacitance of the device.
2) The voltage addition rule does not hold in

this case. When 'S' is a resistor and 'Z' a capacitor (or vice versa) the rule for voltage addition is:

$$V_{in}^2 = V_s^2 + V_z^2$$

3) The inductive reactance of capacitor leads can easily cancel out one or two ohms of capacitive reactance at HF. Keep the leads as short as you can. The effect is much less important with resistors.

TESTING WITH A COMPLEX LOAD

A SUITABLE LOAD MAY be made from a 1 watt resistor and a close tolerance polystyrene capacitor connected in parallel with lead lengths kept very short. The reactance of the capacitor and the resistance of the resistor should not be too different from each other, or from the resistance of 'S'. 'Z' and 'θ' can then be found from the triangle described earlier, and the values of R_p and X_p found. Again, the nominal value of the capacitor will effectively be increased by 4 or 5pF. As explained earlier, the triangle diagram will not tell you whether 'X' is inductive or capacitive. If a capacitor is used as 'S' the method must be modified slightly, but the triangle then indicates instantly whether the load is inductive or capacitive.

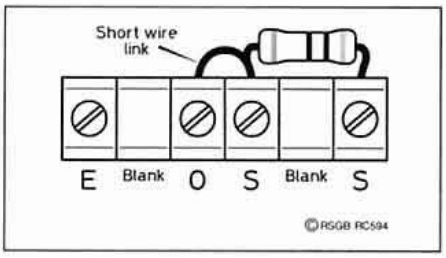


Fig 5: Connector block for the reference components.

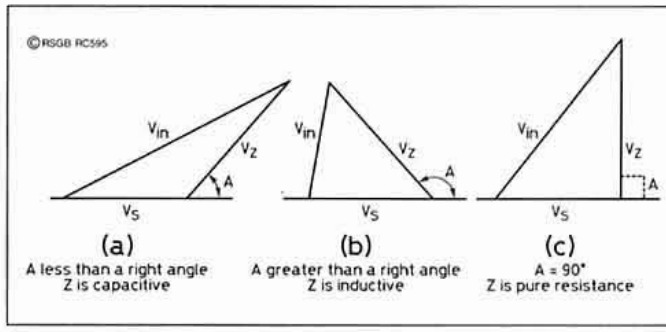


Fig 6: Determination of reactance polarity using a capacitance for 'S'.

USING A CAPACITOR AS 'S'

IF A CAPACITOR OF reactance 'X' is used as 'S'. 'Z' may be found exactly as before:

$$Z = X.\ (V_z/V_s)$$

The method for finding 'θ' is *not* the same. Once again, the voltage triangle is drawn in the same way, and the same angle is measured, but this angle, 'A', in **Fig 6**, is not θ.

θ is equal to either (90-A) or to (A-90), the smaller angle being subtracted from the larger. If 'A' is less than 90° as in Fig 6a the reactive component is capacitive; in Fig 6b the reactive component is inductive. In Fig 6c A=90 which means there is no reactive component and Z is a pure resistance. If Z is a pure capacitance V_{in} is equal to the sum of V_s and V_z, if Z is a pure inductance V_{in} is equal to their difference. If you prefer calculation to drawing a scale diagram, 'O' can be found using

$$\sin\theta = (V_{in}^2 - V_s^2 - V_z^2) / (2V_s \cdot V_z)$$

Note that this is identical to the earlier formula except that it gives Sinθ not Cosθ. This can give both positive and negative values for θ. A positive value indicates a capacitive reactance and a negative value indicates an inductive reactance.

COMPARING CAPACITORS

IF BOTH 'S' AND 'Z' are capacitors there is no need to bother working out reactances. The relation simplifies to:

Unknown capacitance = capacitance of 'S' . (V_S / V_Z).

Note the voltage ratio is 'upside down'. As explained in the next section, the residual output capacitance will need to be subtracted from the measured value of the unknown.

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EUROTEK

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Starting at 28MHz, the coil tap and capacitor setting for best SWR was established. The tuning capacitor was then removed and measured; many modern digital multimeters have a picofarad range. A permanent wire from the coil tap just found to its relay was then soldered in.

A fixed capacitor, of roughly the value just measured but not necessarily of adequate rating, was then soldered in where the tuning capacitor had been unclipped. This must be done because the capacity of this wiring and the open relay will affect the 24MHz band which is set up next. And so on.

As the search time and price of capacitors adequate for 100W was expected to be considerable, it was found best to complete the whole set-up at low power with junkbox capacitors; in the end, two capacitors could be used on three bands each, and those could be made of RG58/U.

If it turns out that an exact capacitor value is hard to get, the next lower value may be shunted by a small capacitor made of coax, or moving the coil tap a bit will effect an adequately low SWR with a standard-value capacitor.

After all bands work satisfactorily on low power, capacitors with the proper ratings are installed and the SWR is checked again, first at the ATU and then at the shack-end of the cable. The SWR in the shack should be the same or a little lower than at the ATU. If all is well, increase power and verify that the automatic ATU can reduce the SWR on all frequencies to where the transceiver will deliver its rated output.

NOTES

[1] If top-band is of interest, two articles are recommended:

'Bring back the end-fed' by G3UCE, RadCom 2/89 (but beware of the under-rated capacitors mentioned!)

'160-m DX from suburban sites' by G3XAP, *RadCom* 12/73.

[2] In the UK, weatherproof plastic cabinets are very expensive. G4LQI's ATU used a wooden platform for the components and an upside-down 2-litre icecream container (held down by a brick) overhanging that platform on all four sides. It survived the 1987 hurricane intact!

[3] Some radios have a band-data output which can be used to select relays in the pre-match ATU through a bought or built interface. The same applies to the antenna selection provisions in some linear amplifiers and automatic ATUs. HB9GBB decodes the BCD band output of his Yaesu transceiver with an SN74LS145 IC, which can sink relay coil currents up to 80mA.

If solid-state devices are used to drive relays, place diodes across their coils to prevent destruction of the switching transistor upon release of the relay.

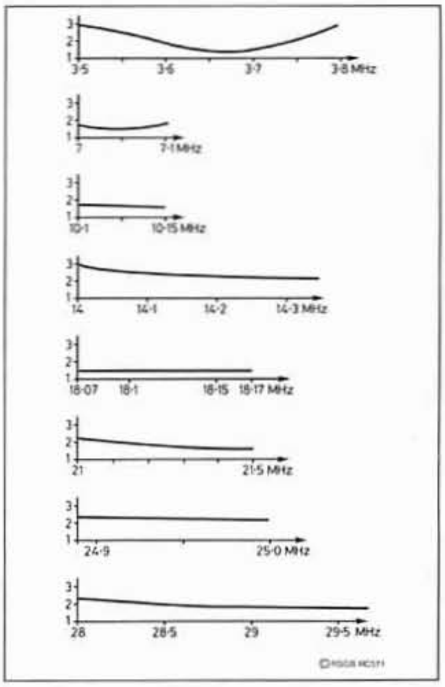

Fig 3: SWR vs frequency in the cable between the remote pre-match ATU and in the shack.

[4] Models with other than 12V coils are inexpensive as surplus and at rallies. The voltage ahead of the regulator in 13.8V linear transceiver power supplies will operate most 24V relays.

[5] 'A real QRPp SWR meter' by DJ1ZB, *Sprat* nr. 69 & 71. ♦

A BOX TO MEASURE RF IMPEDANCES

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ESTIMATING THE RESIDUAL OUTPUT CAPACITANCE

THE MOST CONVENIENT way to do this is to use a capacitor of about 18pF as 'S', and leave the output open circuit. 'Z' is then almost entirely due to the residual output capacitance which can be found in the usual way.

Use a frequency of at least 14MHz. The residual capacitance is typically 4 or 5pF with the coax socket disconnected, and it does not seem to vary much if measured under different conditions.

HARMONICS

THE ONE DISADVANTAGE in the method is that it is susceptible to errors due to harmonic frequencies in the input. If any harmonic present coincides with a resonance of a feeder/antenna system disproportionately large errors could result.

The input should be fed via a simple filter for instance a 1:1 p section filter. Such a filter for 14MHz was made by trial and error using two 470pF capacitors and a self supporting coil of 8 turns, about 2.3cm long and 1.3cm diameter. The filter could be tuned using a dip oscillator and squeezing turns together to obtain the correct filter resonance.

For a frequency 'f' MHz the capacitance should be multiplied by (14/f) though the exact value of the capacitors is not critical.

GENERAL COMMENTS

ACCURACY

It depends upon what is being measured. In general, greatest accuracy is obtained when 'Z' and 'S' are of similar value, when accuracies of 2% or even better can be obtained. In the case of complex impedances where one component is larger than the other.

The most significant component can be obtained to a good accuracy, but the value of the other component may be very approximate. If one of the components is more than 4 times greater than the other, the value of the less significant component is unlikely to be very reliable, and should this figure be 10 or more, the less significant component will probably remain undetected.

VOLTMETER CORRECTIONS

As mentioned before, adding 0.15V to all readings is a reasonable compromise. For readings between 0.5V and 1.0V the correction should be less, and it decreases still more at lower voltages.

The correction is much more significant at lower voltages being a much greater percentage of the reading and therefore having a much greater effect on the final answer. 'S' should be chosen to be roughly equal to 'Z' which means that low voltmeter readings will be avoided. It is probably worthwhile measuring the voltages to the nearest 0.01 volt, even though the last digit will be unreliable.

COMPONENTS

Resistors	
R1	22R
R2, R3	180R, 1W
R4, R5, R6	330K
R7	22K
Capacitors	
C1, C2, C3	1000pF
C4, C5, C6	10nF
Semiconductors	
D1, D2, D3	BAR28, Maplin QQ13P
Additional Items	
Connecting block, Maplin JX38R or JY93B	
Components are available from Maplin Electronic Products, Tel 01702 554161	

ACKNOWLEDGEMENTS

THIS IS A METHOD BASED on similar principles to the Three Meter Method, which gave me some ideas. The technique was first described in QST [1] and by Peter Dodd, G3LDO. [2] [3].

REFERENCES

[1] 'Measurement of R+Xj',D Strandlund, W8CGD, *QST*, June 1965.

[2] 'Measurement of antenna impedance', P Dodd and T Lloyd, *QEX*, Nov 1987.

[3] *The Antenna Experimenters Guide*, available from RSGB Sales, see page 90. ♦